Displacement Sensing with Polymer Fibre Optic Probe

S. Binu[1]*, Jobin George[2]

[1]Department of Opto-Electronics, University of Kerala, Kariavattom, Thiruvananthapuram- 695581, Kerala, India

[2]Department of Physics and Astronomy, University of Calgary, Calgary, Alberta T2N 1N4, Canada

* binuiat@gmail.com

Abstract

The principle of operation, design aspects, experimentation and performance of a polymer fibre optic probe for sensing micro displacement are discussed. The device is based upon the phenomenon of reflective concept. The sensor can work in either the positive slope region or the negative slope region， in addition, it is capable to measure displacement ranging from 0.1 to 0.8 mm with sensitivity of 2.619 V/mm in the positive slope region and 1.3 to 2.9 mm in the negative slope region with a sensitivity of -0.814 V/mm. The simplicity of design, high precision, stability, linearity, high degree of sensitivity, dynamic range, non-contact sensing and low cost of the fabrication make it suitable for real field applications.

Keywords

Displacement Sensor, Fibre Optic Probe, Polymer Optical Fibre

Introduction

High-precision displacement sensors have received significant attention in recent years with the advances in optical engineering, optical signal processing, MEMS and nanotechnology. Potential applications ranging from industrial to medical fields include reverse engineering, micro-assembly, and micro-surgery. In particular, many processes involve distance feedback and hence, the process operation is highly affected by the precision of measurements. The industry, in general, is looking for robust sensors and methods that are compact and less affected by environmental factors. Some applications of inductive, capacitive or piezoelectric sensors are not capable to produce high-quality measurements for industrial use. Among different possible media for measurements, optical measurements offer significant advantages

such as immunity to electromagnetic interference, large bandwidth, high precision, high sensitivity, ease of data processing, efficient communication, flexible circuits, and circuit miniaturization and so on. In terms of size, weight, response, sensitivity, environmental conditions etc., the fibre optic displacement sensor is much superior to traditional displacement sensor. There are two methods of non contact displacement measurement using fibre optic sensors: phase modulated sensors and intensity modulated sensors. Though a high resolution is achievable, interferometric methods are cumbersome in signal processing compared to the intensity modulation techniques [Zubia et al.,2001, Puangmali et al., 2010, Binu et al., 2010, Binu et al., 2006, Shelly John et al., 1997].

Recently, polymer optical fibres have become an important part of sensor technology. Polymer optical fibres are more flexible than silica optical fibres and possess a high fracture toughness that makes them ideal for large strain applications. The Young's modulus of typical polymer optical fibres is much less than that of silica optical fibres. Silica optical fibres are brittle in nature which makes them more susceptible to impact and abrasion damage. A polymer coating is required to protect the surface from scratches, cracks and possible fracture. Polymer optical fibres do not require such a jacket due to their high fracture toughness. Additionally, polymer optical fibre may offer other significant advantages, such as excellent light delivery, long interaction length, large diameter up to 1000 μm, immunity to electromagnetic interference, free from heating effect during transmission, immunity to vibrations, minimum attenuation at the operating wavelength of 660 nm, simpler and less expensive components, lighter weight, greater flexibility, high numerical aperture, which facilitates handling and light coupling, low cost and ability not only to excite the target molecules but also to capture the emitted light from the targets. Their use as a probe or as a sensing element is increasing in clinical, pharmaceutical, industrial and military applications [Koeppen et al., 1998, Kiesel et al., 2008,

Zhou et al., 2009, Montero et al., 2009, Binu et al.,2009,]. Fibre optic probe contains a bifurcated fibre bundle, a fibre bundle with transmitting and receiving fibres arranged in random, concentric and semi circular configuration or large core polymer optical fibres. The sensitivity and dynamic range of such sensors are dependent on the geometrical arrangement of the array of fibres. The displacement sensing is one of the most fundamental measuring methods because a number of measurements such as amplitude of vibration, target reflectivity, concentration, temperature, pressure etc., can be reduced to displacement sensing [Chu et al., 2012, Bilro et al., 2012, Binu et al., 2007, Vengal Rao et al., 2012]. Among the various applications of polymer optical fibre in the field of fibre optics, their use for sensing micro displacement is of interest. In this paper, a simple, rugged, low cost and very efficient polymer fibre optic probe is proposed for sensing micro displacement.

Experiment

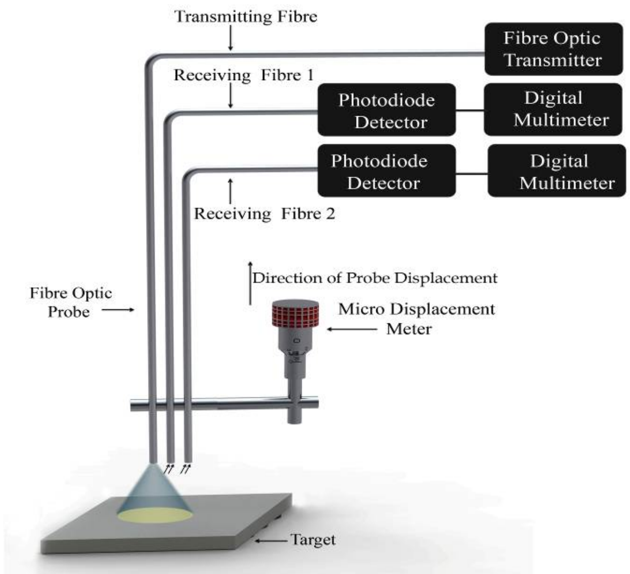


Figure 1: Schematic representation of fibre optic micro displacement sensor

The schematic representation of the fibre optic displacement sensor is shown in figure 1. The device consists of fibre optic transmitter, fibre optic probe, target, photodiode detector and digital multimeter. Fibre optic transmitter (SFH 756V) is an attractive choice as optical source in intensity modulated sensors because of its low cost, high reliability, stable and consistent output for longer periods in comparison to laser diode, emission in visible region (λ = 660 nm), 2.2 mm aperture which holds standard 1000 micron plastic fibre, good linearity, molded micro lens for efficient coupling and plastic connector housing, resulting in safe handling. The fibre optic probe consists of three 50 cm length PMMA (polymethyl methacrylate) fibres with diameter 1 mm, numerical aperture 0.5, core refractive index 1.492 and cladding refractive index 1.402. The three fibres are parallel to their axes with a particular spacing between them (1 mm). Two receiving fibres are arranged side by side to operate in the positive and negative slope region. The fibre optic probe used is intensity modulated extrinsic sensor with advantages like small size, light weight, geometrical versatility, EMI immunity, easiness of multiplexing and demultiplexing. The target consisting of a square piece of copper plate of dimension 3 cm, is polished as follows, then sanded on a sanding block until all visible machining marks are removed. Once the deep scratches are removed, the surface is wet polished with sand paper. The sample is then polished on a rotating wheel with a 12 μm diamond polishing compound for approximately five minutes followed by polishing for two minutes with a 4 μm compound. Once the sample is cleaned with distilled water, it is ready to be mounted for static calibration. The photo diode IF-D91 is a high speed photodiode detector housed in a “connector-less” style plastic fibre optic package. Optical response of the IF-D91 extends from 400 to 1100 nm, making it compatible with a wide range of visible, infrared LED and laser diode sources. This includes 650 nm visible red LEDs used for optimum transmission in PMMA plastic optic fibre. The detector package has an internal micro-lens and a precision- molded PBT housing to ensure efficient optical coupling with standard 1000 μm core plastic fibre cable. The fast response time of the IF-D91 makes it suitable for high speed digital data links. When used with an appropriate LED or laser diode source, the IF-D91 is capable of 100 Mbps data rates. The integrated design of the IF-D91 provides simple, cost effective implementation in a variety of analog and digital applications. The target surface to be measured is placed in front of the fibre optic probe with a gap such that the reflected light spot image covers the core of the receiving fibres. The micro level static displacement measurement is carried out to calibrate the fibre optic probe by properly calibrating the

detected voltage. Mounted on a micro displacement meter (resolution 1 μm) which is rigidly attached to a vibration free table, the static displacement of the fibre optic probe is achieved. The fibre optic probe is held perpendicular to the target. The position of the micro displacement meter is adjusted until fibre optic probe is brought in close contact with the target. Light from the fibre optic transmitter (peak wavelength at 660 nm) is coupled into the transmitting fibre. The signals from the receiving fibres are measured by moving the probe away from the zero point, where the target and the probe are in close contact. The signals from the detectors are converted into voltage and measured by a digital multimeter. The output intensity is measured by changing the position of the fibre optic probe from 0 to 8 mm in a step of 10 μm.

Results and Discussion

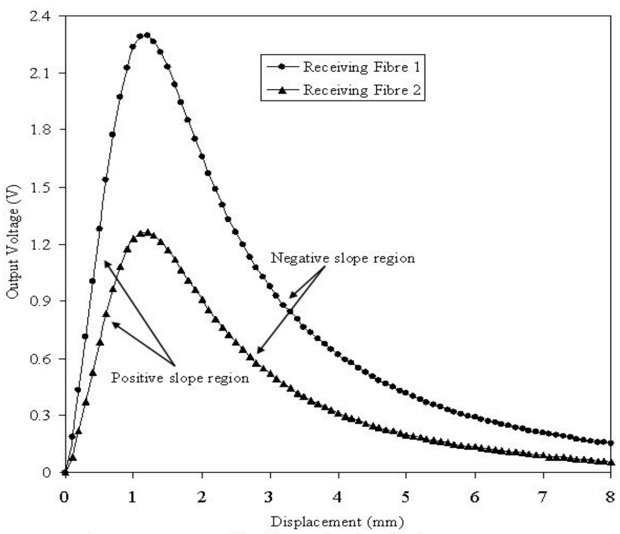
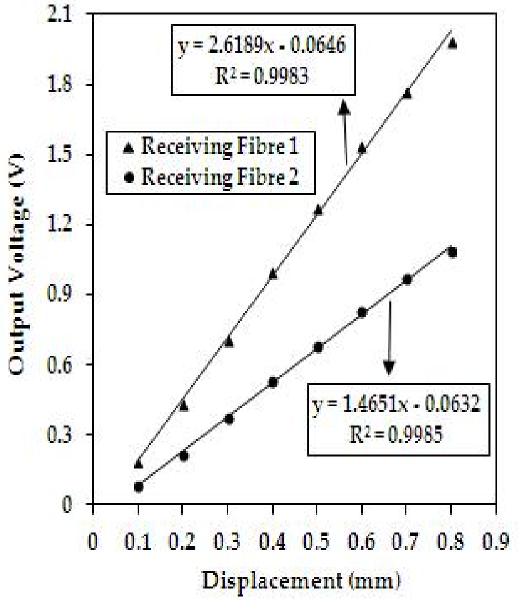


Figure 2: Response of the fibre optic micro displacement sensor

Figure 2 shows the variation of output voltage with displacement for receiving fibres 1 and 2. When the probe is in close proximity to the reflective surface, the amount of reflected light is very small. However, as the fibre optic probe moves further away from reflective surface, the amount of light seen by the receiving fibres increases rapidly. Even micrometer movements of fibre optic probe cause a significant increase in the reflected light and a sharp increase in the output voltage. As shown in figure 2, a steep curve incline occurs in this range. This highly sensitive area is referred to as the positive slope region of the calibration curve. Further movement of the target from the probe causes the illuminated area to enlarge, increasing the amount of reflected light seen by the receiving fibres. Eventually light is saturated when the receiving fibres accept the maximum amount of light for their dimension. At this point, the maximum amount of light is transmitted to the sensor and the maximum output voltage is generated. The calibration curve then reaches the apex of the instrument response, which is called the optical peak. The displacement range over which the initial rise in signal and the maximum occurs is primarily determined by the diameter and numerical aperture of the fibres. The output after reaching the maximum starts decreasing for larger displacements due to large increase in the size of the light cone as the power density decreases with increase in the size of the cone of light. This less sensitive area is referred to as the negative slope region of the calibration curve. Figures 3 and 4 shows the linear range of the sensor in the positive and negative slope regions respectively. The positive slope region is highly sensitive and useful for close distance target and the negative slope region is less sensitive and useful for long distance. The slope is used to determine the sensitivity of the sensor. As shown in figure 3, in the positive slope region, the sensor achieves sensitivities of 2.619 and 1.465 V/mm for receiving fibres 1 and 2 respectively over the range of 0.1 to 0.8 mm. Similarly, as shown in figure 4, in the negative slope region, the sensor achieves sensitivities of -0.814 and -0.458 V/mm over the range of 1.3 to 2.9 mm. The sensor shows a very good linearity in both regions as shown in figures 3 and 4. Table 1 lays out the performance characteristics of the fibre optic displacement sensor. In order to measure the time stability of the sensor, the experiments are repeated at an interval of 2 h over a period of 12 h. It is found that the output intensity varies only less than 0.001% for identical conditions during this interval. The possible sources of error in sensor operation can be due to light source fluctuation, stray light and possible mechanical vibrations. To reduce these effects, a well-regulated power supply is used for the light source and this minimizes the fluctuation of source intensity. The sensor fixture is designed so that the stray light cannot interfere with the source light and ambient light does not have any effect on the output voltage. To reduce the mechanical vibrations, the experimental set-up is placed on a honeycomb structured vibration free table. Other environmental parameters such as air pressure, temperature and humidity do not have any noticeable effect on the measurements reported here. If the emitting and receiving fibres are put exactly normal to the reflecting surface, the reflected light may enter the emitting fibre and impact the stability of the source

especially in the case of high power sources being used.



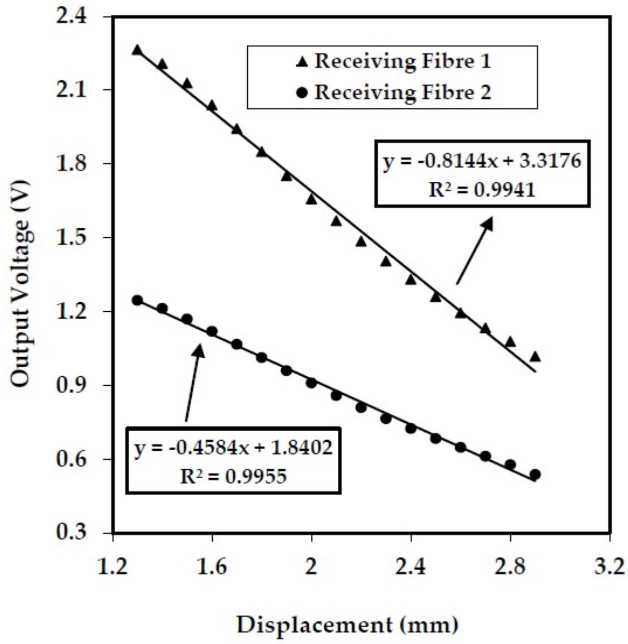


FIG. 3 LINEAR RANGE OF THE SENSOR IN THE POSITIVE SLOPE REGION (LINEARITY R^2 IS NEARLY EQUAL TO 1)

FIG. 4 LINEAR RANGE OF THE SENSOR IN THE NEGATIVE SLOPE REGION (LINEARITY R^2 IS NEARLY EQUAL TO 1)

TABLE 1 PERFORMANCE CHARACTERISTICS OF THE FIBRE OPTIC DISPLACEMENT SENSOR

Receiving Fibre	**Peak Voltage (V)**	**Positive slope region (0.1 to 0.8 mm)**		**Negative slope region (1.3 to 2.9 mm)**	
		Linearity	*Sensitivity (V/mm)*	*Linearity*	*Sensitivity (V/mm)*
1	2.296	0.9983	2.619	0.9941	-0.814
2	1.265	0.9985	1.465	0.9955	-0.458

Conclusion

A simple, rugged, low cost and very efficient polymer fibre optic probe has been designed and fabricated for sensing displacement based upon the phenomenon of reflective concept. The sensor is capable to measure displacement ranging from 0.1 to 0.8 mm in the positive slope region and 1.3 to 2.9 mm in the negative slope region. The capability of fibre optic sensor to work close to the reflecting surface without the need for special optics is especially advantageous for embedded sensor applications. The stable sensor is ideal for use as an embedded sensor, requiring minimal maintenance even in relatively harsh environments. The simplicity of design, high precision, stability, linearity, high degree of sensitivity, dynamic range, non-contact sensing and low cost of the fabrication make it suitable for real field applications. Additionally, reduced size of a sensor could create new applications by allowing the sensor to be embedded into small areas. The sensor having a wide linear operating range can be designed for optimum performance by choosing the fibre diameter and numerical aperture. Moreover, accuracy and reliability are the excellent pay-offs of this fibre optic sensor.

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S.Binu received the M.Phil degree in Physics from the Alagappa University, Karaikudi, India and Ph.D. in Opto-Electronics from the University of Kerala, Thiruvananthapuram, India. He has worked as a postdoctoral researcher in the Department of Opto-Electronics, University of Kerala, India, Department of Physics, Indian Institute of Technology Delhi, New-Delhi, India, Department of Electro-Optical Engineering, National United University, Taiwan 360 (ROC) and currently he is working as a Research Associate in the Department of Physics, Indian Institute of Science Education and Research, Bhopal, India. His research interests include chalcogenide photonics, fibre optic sensors and devices.

Jobin George was born in Kerala, India on January 20, 1985. He received his B.Sc degree from Kerala University, India in 2006 and the M.Sc. degree in applied physics from Mahatma Gandhi University, Kottayam, India, in 2008. He joined the fiber optics group, Department of Physics, Indian Institute of Technology Delhi in 2009 and engaged in optical parametric oscillator and optical fiber sensor research. He joined Institut für Optik und Quantenelektronik, Friedrich-Schiller-Universität Jena, Germany in 2010 and engaged in Terahertz research. In 2012 he joined the Department of Physics and Astronomy, University of Calgary, Canada as a graduate student and until now he is working on his thesis on spectroscopy of van der waal complexes.